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AGARD ADVISORY REPORT NO.267

Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Computational Methods for Aerodynamic Design (Inverse) and Optimization

(Les Méthodes de Calcul pour la Conception Aérodynamique (Méthodes Inverses) et l'Optimisation)

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.267

TECHNICAL EVALUATION REPORT

on the

FLUID DYNAMICS PANEL SYMPOSIUM

on

Computational Methods for Aerodynamic Design (Inverse) and Optimization

(Les méthodes de calcul pour la conception aérodynamique (méthodes inverses) et l'optimisation)

by

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This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Exchange of scientific and technical information;
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Published April 1990

ISBN 92-835-0557-3

*Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ*

Foreword

The Fluid Dynamics Panel of AGARD organised a Specialists' Meeting on the subject of "Computational Methods for Aerodynamic Design (Inverse) and Optimization". The Specialists' Meeting was motivated by the observation that "design type" of CFD (Computational Fluid Dynamics) methods appear to receive relatively little attention as compared to "analysis type" of methods; this in spite of the fact that the "design type" of methods offer unique possibilities for which there is no equivalent in experimental aerodynamics.

The Program Committee for the meeting is grateful that Mr Preston Henne of McDonnell Douglas Corporation, Douglas Aircraft Company accepted the invitation for acting as the Technical Evaluator of the meeting, in particular because he combines a detailed knowledge of "design type" CFD methods with a vast experience in aerodynamic design in an industry environment. The present report contains his observations, remarks and comments on the meeting. The 23 papers presented at the meeting have been collected in AGARD Conference Proceedings CP 463.

*   *   *

Le Panel AGARD de la Dynamique des Fluides a organisé une réunion de Spécialistes sur "Les méthodes de calcul pour la conception aérodynamique (méthodes inverses) et l'optimisation". En effet, le Panel a constaté que les méthodes CFD (l'aérodynamique numérique) pour la conception suscitent relativement peu d'intérêt par rapport aux méthodes pour l'analyse, et ceci malgré le fait que les méthodes pour la conception offrent des possibilités uniques, pour lesquelles il n'existe aucun équivalent dans le domaine de l'aérodynamique expérimentale.

Le comité du programme de cette réunion tient à remercier M. Preston Henne de la McDonnell Douglas Corporation, Douglas Aircraft Company, pour avoir bien voulu accepté d'exercer les fonctions d'Expert technique pour cette réunion. Le comité se félicite sur son choix d'expert, puisqu'il s'agit de quelqu'un qui sait allier des connaissances approfondies des méthodes CFD du type "conception" à une vaste expérience dans le domaine de la conception aérodynamique, dans un contexte industriel.

Ce rapport contient ses réflexions, remarques et commentaires sur la réunion. Les 23 communications présentées lors de la réunion ont été rassemblées sous la forme du Compte-rendu de Conference AGARD CP 463.

J.W.Slooff
Editor

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AGARD FLUID DYNAMICS PANEL - 64th MEETING

SPECIALISTS' MEETING ON

COMPUTATIONAL METHODS FOR AERODYNAMIC DESIGN
(INVERSE) AND OPTIMIZATION

LOEN, NORWAY
22-23 MAY 1989

by

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1.0 SUMMARY

The papers presented at the AGARD Specialists' Meeting on Computational Methods for Aerodynamic Design (Inverse) and Optimization are reviewed. Strengths and weaknesses are identified for many of the contributions as each is reviewed. The reviewer closes with some general comments.

2.0 INTRODUCTION

The 64th Meeting of the AGARD Fluid Dynamics Panel included a Specialists' Meeting on 22-23 May, 1989. The Specialists' Meeting was entitled "Computational Methods for Aerodynamic Design (Inverse) and Optimization." The Program committee, Appendix A, identified the theme for the meeting as the following:

"Computational Fluid Dynamics (CFD) play an increasingly important role in aerodynamic design. From the design applications point of view two catergories of CFD-based design methodology may be distinguished.

The first utilizes analysis type methods in an heuristic/empirical cut-and-try type of process. In this kind of process the role of CFD is to predict the aerodynamic characteristics of a configuration (or part thereof) of given geometry provided by the designer. The second category of CFD-based methods addresses the problem of design for aerodynamic characteristics in a more direct sense. Examples are (the classical) inverse methods which provide the detailed geometry required to generate a given pressure distribution and methods utilizing numerical optimization techniques to obtain the geometry that minimizes, subject to constraints, a given aerodynamic objective function such as drag, load distribution, etc.

The purpose of the Specialists' Meeting is to stimulate communication on recent developments and current research on the second category of methods (i.e. inverse methods and methods utilizing numerical optimization techniques)."

The Specialists' Meeting was organized into the following four sessions:

Session I - Invited and Survey Papers

Session II - Inverse Methods / Airfoils and Wings

Session III- Inverse Methods / Turbomachinery, Intakes, Ducts

Session IV - Numerical Optimization

The full listing of authors and papers is included in Appendix B. The paper number, shown in Appendix B and utilized in the discussion below, is the number assigned by the program committee and does not represent the order of the program presentations.

3.0 SESSION I - INVITED AND SURVEY PAPERS

In this introductory session four presentations were made. The papers of Sobieczky, Bocci, and Koster et. al. were available at the meeting. The fourth presentation, that of Jameson, was an oral briefing only. The focus of this introductory session was largely on airfoils and wings. The technical range and contrast of the papers in this session was quite large. The presentations included reviews of remarkably elegant and new design methods as well as applications of traditional methods with reportedly disappointing results. The variation in success reported in these introductory papers was larger than expected.

PAPER 1. SOBIECZKY provided the extended introductory presentation and focused on flowfield characteristics, particularly as inferred from hodograph plane analyses. The printed version of the Sobieczky paper highlights the different design method approaches. These approaches are the hodograph method, the inverse method, and parametric or numerical optimization. The written version of the paper contains a brief summary of recent work in each category of design method approaches.

In the inverse method area in particular, the Euler equation airfoil design method of Drela[1] was highlighted. The Drela method is a novel approach to airfoil design that is a natural extension of the streamline oriented numerical scheme originally developed for an analysis method. The work of Takanashi[2] is also mentioned. Takanashi utilized an approach based on a residual-correction scheme coupled to transonic integral equation. The advantage of this approach is that the geometry correction scheme can be maintained separate and distinct from the flow solver. The flow solver is treated as a "black box". Hence, the scheme is applicable in principle to many existing analysis methods.

Numerical optimization works of Consentino and Holst[3] and of Gregg and Misegades[4] are mentioned. Consentino and Holst utilized a gradient search strategy in combination with a parameterized definition of a portion of a wing surface. The objective function for the numerical optimization was lift-to-drag. Gregg and Misegades performed similar wing optimization but utilizing an evolution theory numerical scheme in place of a gradient based method. The advantage reported for the evolution theory scheme is the ability to handle a large number of design variables, coupled design variables, complex constraints, and step functions.

Sobieczky closes his paper with a forecast dealing with Artificial Intelligence and Expert Systems. Sobieczky states that progress should be expected in the development of Aerodynamic Expert Design Systems in the near future.

PAPER 3. BOCCI presented a review of airfoil design techniques and design exercises accomplished at the Aircraft Research Association Limited (ARA) over a number of years. Design studies of a combat wing airfoil, a transport wing airfoil, laminar flow airfoils, and propeller blade airfoils are reviewed in a summary fashion.

This paper, different from any of the other presentations made at the conference, seemed to be quite negative on the use the recently developed design methods. Examples are shown which are reported to be failures of the design methodology, particularly inverse supercritical methods. However, in light of a growing volume of work to the contrary and reported by user agencies (see References 5-10 as a quick sample), this position seems difficult to understand. Bocci's paper seems out of line with current capabilities and the state-of-the-art in design methodology. Review of the other papers at this conference also support such a view.

PAPER 7. KOSTER et.al. provided only hard copies of viewfoil art at the time of the conference. Hence, it is somewhat more difficult to critique such an effort. In the presentation reference was made to at least five different design methods used at the DRL-Institute for Design Aerodynamics, FRG. This reference indicates a strong commitment to design methods at DRL. Examples were presented for an airfoil application and a nacelle cowl development. Koster makes the point that four essential parts are needed for the design process: (1) detailed and accurate description of the design requirements, (2) design methods for providing the basic shape and for carrying out small changes, (3) analysis methods to confirm the design and estimate the off-design behavior, and (4) experience in the use and combination of results from design and analysis methods in order to perform a successful design. The fourth item cannot be overemphasized. The finest methods available today still demand application experience if they are to be used with confidence.

PAPER 22. JAMESON presented an oral review of recent work that he has accomplished in the area of aerodynamic design. Specifically, Jameson has developed a design method approach by applying control theory to the problem. He treats the design problem as a control problem in which the control is the shape of the aerodynamic surface. By using control theory a target pressure distribution can be sought while additional quantities such as drag can be minimized simultaneously.

The elegant mathematical formulation presented by Jameson is clearly the product of some creative thinking focused on the the aerodynamic design problem. Jameson indicated that such a scheme has been mathematically derived for two-dimensional potential flow, two-dimesional Euler flow, and three-dimensional Euler flow. Computational implementation of the scheme has been accomplished for the two-dimensional flows. Examples were shown that illustrate a significant potential for the method. A drawback of the scheme as it currently stands is the computational time involved. Each iteration of the scheme requires about the time of two flow solutions. A second differential equation, the adjoint equation with its related boundary conditions, must be solved along with a standard potential equation or Euler equation solution in each geometry iteration. If 5 to 10 geometry iterations are required for convergence, then the process is roughly equivalent to 10 to 20 analysis solutions. Nevertheless, this approach represents a fresh look at the design problem and numerous researchers are likely to adopt it.

4.0 SESSION II - INVERSE METHODS / AIRFOILS AND WINGS

PAPER 2. VOLPE discussed recent work assisted with transonic airfoil design. The theme of his presentation was based on highlighting various approaches to satisfying Lighthill's three constraints. The three constraints are associated with freestream consistency and orthogonal trailing edge closure of the designed airfoil. Volpe has shown that these constraints can be introduced into the design problem in an number of ways and has used the Dirichlet boundary condition (transpiration scheme) in a 2-D potential solution to demonstrate the approach. A number of sample applications, both subsonic and transonic, of the design scheme were presented. Details were presented that substantiate the method as being a well developed and matured capability.

PAPER 4. MALONE presented results for an application of a residual-correction approach coupled to a 2-D Navier-Strokes code. As discussed in the written version of the paper, this approach allows the geometry correction scheme to drive the analysis code as a "black box". The title of the paper is "An Efficient Airfoil Design Method Using the Navier-Stokes Equations". Clearly this work is one of the earliest attempts at using the N-S equations in an inverse method application. Reported solutions utilized several thousand flowfield iterations for convergence. This magnitude of resource use indicates a different definition of efficiency when compared to that associated with potential solution schemes.

Three example applications are shown in the paper. The first two demonstrate solution convergence while the third represents a more typical design application. Examination of the results for the third application reveals that a target pressure distribution, defined parametrically a priori, was closely achieved in the design process. However, the resulting airfoil shape would appear to have an unusual shape near the leading edge and a surface wiggle at the shock position on the upper surface.

It was the reviewer's hope that the author had actually attempted a design at massively separated flow conditions, thus justifying the use of the N-S set of equations. Unfortunately, this was not the case and only an attached flow case was presented at this time. Future efforts would be expected for separated flow conditions in order to justify N-S application.

PAPER 5. FORNASIER described a progress report on inverse capability using a higher-order panel method for arbitrary aircraft configurations at subsonic and supersonic speeds. The panel method is based on mixed boundary conditions of Dirichlet and Neumann type. Inverse capability is introduced by defining additional singularity distributions in an iterative fashion to drive an initial configuration to a new configuration with a specified pressure distribution. Examples are presented in the written paper for a 2-D airfoil case and for a 3-D body case. In both cases convergence toward the correct geometry for a corresponding target pressure distribution is demonstrated. Detailed review of the results still pointed out some modest discrepancies, according to the author, and future efforts are directed at further generalizing the geometry handling procedures.

PAPER 6. BRANDSMA presented a scheme for transonic wing design based on a residual-correction approach. In this scheme an initial 3-D wing geometry is used to create an initial pressure distribution using the transonic analysis code XFLO22. A target pressure distribution is specified and compared to the initial pressure distribution. This comparison yields a pressure difference referred to as a defect pressure. This incremental Cp is transformed into an equivalent subsonic incremental velocity which is imposed on a 3-D subsonic inverse panel method based on *mean plane singularity* distributions. Further constraints can be imposed on camber and thickness and a least squares solution is obtained to minimize the pressure defect as well as deviations from the imposed geometrical constraints. A single sample applicaton was presented in which a known wing geometry was recovered for a known target pressure distribution. The results after six geometry iterations were shown. Convergence to the correct geometry is indicated. Some residual sensitivity in the root region of the wing is indicated in the results.

PAPER 8. DE PONTE presented an approach utilizing the ficticious gas concept in connection with a field panel method for compressible 2-D flows. The author claims that the field panel approach offers a simpler way of introducing compressibility effects. However, examples of flow solution convergence were presented that indicated large oscillations. Further, the author indicated that these oscillations were 'FORTRAN compiler dependent". The author did present an example calculation of a 2-D airfoil modified to be shock free with the ficticious gas scheme. While the combination of ficticious gas and field panel flow solutions may be unique, the work seemed rather sketchy and perhaps reported prematurely.

5.0 SESSION III - INVERSE METHODS / TURBOMACHINERY, INTAKES, DUCTS

PAPER 9. VAN DEN BRAEMBUSSCHE made copies of his paper available at the conference but was unable to be at the conference for the formal presentation. A review of the paper does indicate a successful approach for cascade blade design was developed. The approach utilizes a decoupled flow solver and geometry modifier. The geometry modification scheme is based on a surface distribution of vortices to drive an initial velocity distribution towards a specified target distribution. The vortex distribution is used to define a normal flow which in turn is used in a mass flux integral or streamline slope integral to define the new geometry shape. Examples are presented which utilize both an incompressible potential flow solver and time-marching Euler solver. Recovery of a known shape with a known velocity distribution is demonstrated as one of the expamples.

PAPER 10. CETINKAYA reviewed the development of an Euler based design method for airfoils and cascades. A steady, 2-D Euler code, based on a streamline coordinate system and a finite volume technique, is used in the method. The scheme is seen to be very similar to that of Drela. Free parameters are introduced into the specified pressure distributions to account explicitly for Lighthill's constraints. By imposing a specified wall pressure distribution as a boundary condition in the streamline calculation, the new surface geometry evolves as part of the solution convergence. Three examples are presented which show consistent recovery of known cascade and airfoil geometries for known prescribed pressure distributions. These examples included initial geometries exhibiting embedded shocks and driving these geometries to supposedly shock free flows.

PAPER 11. SCHMIDT described the use of a method based on flows calculated on stream surfaces of revolution. The flow solution uses the full potential equation transformed into the potential-stream-function plane. The discretized solution is performed using successive line overrelaxation and accelerated with a multigrid scheme. Unfortunately, details of the inverse scheme implementation are obscure. Difficulties relative to "ill-posedness" are mentioned. The author does, however, indicate use of design a^ off-design flow conditions as a means of improving off-design operational behaviour. This is an approach to what is in reality a multi-point design problem. The author also provides at least a single pressure distribution correlation between a design computation and corresponding experimental measurement. This correlation does indicate a good measure of agreement.

PAPER 12. JACQUOTTE presented an inverse scheme for quasi-three-dimensional flows through axial cascades. The flow solution is based on the potential equation and is solved using a finite element approach. In this scheme the inverse capability is implemented using the Dirichlet boundary condition approach to impose the specified pressure distribution. The resulting solution normal flow to an initial surface is integrated to produce a surface displacement of the initial geometry. Both C-mesh and H-mesh grid systems are demonstrated. This author also demonstrates recovery of a known geometry. This recovery, including the convergence, is illustrated for several different starting points. This result tends to indicate the proper handling of Lighthill's constraints. Other examples are also presented to indicate that apparently arbitrary pressure distributions did produce quite reasonable looking airfoil sections. However, no other results to validate performance levels for the designed sections are presented.

PAPER 13. BORGES described a three-dimensional inverse method to define a radial inflow turbine. The method applies to incompressible and inviscid flows and assumes that the blades are infinitely thin. The thin blade assumption allows the blades to be modelled by surface vorticity. The blade shape is defined by aligning the mean line with the local velocity. Since this velocity depends on the vorticity distribution the solution is iterative.

This author was one of the few which utilized an inverse scheme to define an aerodynamic configuration which was experimentally validated. The author is commended on the thoroughness of the paper and the completeness of the technical project. The experimental confirmation of an improved impeller design is a confirmation of a good computational approach to a difficult three-dimensional problem.

PAPER 14. ZANNETTI presented a method for the design of three-dimensional blade rows for turbomachinery applications. The scheme utilized an Euler equation solution employing characteristics theory. The blade loading is imposed in the inverse solution and the blade camber is calculated.

6.0 SESSION IV - NUMERICAL OPTIMIZATION

PAPER 15. RIZK described an approach to aerodynamic optimization in which the iterative solution of the flow equation and the design parameter optimization are conducted simultaneously. This rather interesting approach avoids independent, and correspondingly time-consuming iterations of the flow solution and the design parameters. The approach is demonstrated for a wind tunnel wall interference study and for a propeller design study. The rate of convergence of the optimization problem appears to be greatly enhanced by this simultaneous approach. The examples presented indicate that the optimization can be accomplished at a cost of roughly 1L to 4L times the cost of a regular analysis solution where L is the number of design variables. The promise of such an approach should be pursued with further studies of the influence of large numbers of design variables and the effect of the convergence speed of the underlying analysis method.

PAPER 16. VAN DEN DAM presented a summary of a spanload optimization approach currently implemented at NLR. The scheme represents a unified approach for the preliminary design of multiple lifting surfaces. Propeller influences on spanloads are also included. Optimization is performed using a Trefftz-plane evaluation of induced drag plus form factor methods for viscous airfoil drag. Minimization of induced drag or induced drag plus viscous drag can be accomplished subject to constraints on items such as lift, moment, and airfoil characteristics. The method is demonstrated for numerous configurations including canard and three-surface configurations, and wing tail variations. The method is clearly a valuable preliminary design tool. It is an accumulation of a number of classical procedures that many aircraft companies utilize in one manner or another. The present approach would appear to be the result of a conscious effort to cast these preliminary design procedures in a consistent optimization format with considerable flexibility.

PAPER 17. VAN EGMOND described the development and application of parameterized airfoil pressure distributions that serve as target pressure distributions for inverse design studies. This approach has been developed to help systematically answer the question as to what is the correct pressure distribution to specify in an inverse design problem. The parametric representation of an airfoil pressure distribution is reviewed. Several means of numerical optimization are provided. The method consists of the parametric pressure distribution representation, boundary layer calculations for viscous drag, a simple formula for approximate shock drag, and an approximate means for constraining airfoil thickness based on a pressure distribution integral. Since these ingredients are relatively simple and inexpensive in terms of computational resources, many iteratons can easily be accomodated in the optimization scheme.

The typical use of this method would seem to be initiated with an analysis solution on an existing airfoil. A parametric best fit of the resulting pressure distribution is computed. This best fit distribution is then numerically improved ("optimized") using the elements described above. The final pressure distribution is then used as an input target pressure distribution using an inverse design method. Example applications to laminar flow airfoils, a Liebeck high-lift airfoil, and a transonic airfoil are described. Only calculations are presented; no experimental verification is demonstrated. In fact, the differences in lift and drag shown for the optimized airfoil configurations are small and may be within the computational and experimental error band.

This scheme begins to resemble an approach in which an inverse airfoil code is iteratively driven by a parametric pressure distribution which is itself driven simultaneously by a numerical optimization scheme. Such an approach seems highly desirable to the reviewer. However, the NLR scheme presented by Van Egmond does NOT drive an inverse code during the numerical otimization. Instead it makes use of the approximate elements described above and upon completion of the optimization makes use of the inverse solution only once. While the NLR approach is clearly an economical one, the additional aproximations introduced may limit its utility in cases of small refinements.

PAPER 18. GHIELMI provided a description of a numerical optimization scheme for airfoils at multiple operating points. The scheme utilized the well known CONMIN algorithms as the design parameter driver. Explicit algebraic shape functions are used to perturb the airfoil contours. Specific reference is made to the emphasis on the use of constraints rather than a complicated objective function. The example presented was an airfoil design problem for a military trainer with two transonic design points. The flow solver used in this effort was the two-dimensional potential solver, FLO6, of Jameson. Additionally, the author in the written paper makes mention of the use of expert system programming to effectively implement the scheme and retain man-in-loop capability.

PAPER 19. RENEAUX described an approach similar to the previous paper. The ONERA scheme is based on the application of CONMIN combined with the two-dimensional airfoil analysis method of Garabedian and Korn. The numerical optimization scheme was applied to a helicopter rotor design problem. The scheme was first used to develop improved airfoil sections using two design points. One point corresponds to an advancing blade condition, while the second point corresponds to a retreating blade condition. The blade section improvements that were computationally developed were experimentally verified by wind tunnel test. The improvements are significant enough to be well beyond the computational and experimental error band. Consequently, the investigators had a high probability of success. The authors are to be commended for the completeness of the airfoil optimization effort.

A second numerical optimization application is also demonstrated. The second application uses the same optimizer coupled to a rotor performance method based on blade element theory. It is emphasized that such an approach is attractive due to the many flight conditions and constraints which must be observed in the rotor design process.

PAPER 20. BOCK presented a summary of numerical optimization cases including a supersonic airfoil section, a supersonic body of revolution, a transonic airfoil, and a subsonic multi-element high-lift airfoil. The paper appears to be a thorough documentation of these examples and indicates attention being paid to real design problems. Clearly, the author has found that a numerical optimization approach offers value to the aerodynamic designer.

The author did, however, indicate several points which deserve some attention. First, an initial comparison is made between gradient methods and evolution methods for numerical optimizers. The conclusion is reached that the gradient method is far superior as a result of the extended number of iterations required by the evolution method. While the conclusion may be correct for specific problems, this implementaton of the evolution method would appear to be such that an inefficient search is accomplished. The evolution method should be a trivial scheme to implement and has been shown to converge rapidly in other investigations. Second, in the transonic airfoil case a numerical optimization scheme is presented in which the design variables include an upper surface bump function defined by a ficticious gas scheme to drive towards a shock-free airfoil contour. Such an approach is believed by the reviewer to be overly constraining. The ficticious gas scheme is an interesting academic exercise but does not provide design capability for the entire airfoil surface. Instead, it focusses on the supersonic bubble and the attainment of shock-free flow. Airfoils designed for shock-free flows are notorious for poor off-design behaviour. Consequently, a better optimization can be accomplished if the scheme addresses the issue of shocked flows at multiple design points. Third, an observation is made that convergence of the objective function is not clear for several of the cases presented.

PAPER 21. DESTARAC reviewed examples of numerical optimization for transonic wing design problems. Preliminary efforts relating two-dimensional and three-dimensional results provide an indication of the background utilized in the wing examples presented. The three-dimensional wing optimizations presented include the development of the inboard area of a three-dimensional swept wing and the development of local treatments required to integrate wing mounted nacelle/pylon configurations. These two problems are classical wing aerodynamic design problems. The results presented for numerically optimized configuration variations indicate a rapid means to develop improved geometry solutions for these problems. The convergence results presented in this paper indicate significant convergence is indeed being obtained by the numerical optimization scheme.

PAPER 23. HUDDLESTON presented the progress on a rather unique application of numerical optimization coupled to a CFD method. This applicaton is targeted at the development of a simulation for engine inlet testing in a ground-based facility. The simulation is to provide an inlet onset flowfield that best matches that which a fighter vehicle forebody can create. One of the unique aspects of this work is that the optimization objective function is based on off-body flow variables. A least-squares type of evaluation is used to make the evaluation of the objective function consistent with the design variables implemented. Three test cases are reviewed in which the off-body, least-squares approach is used to recover a known and consistently generated target solution. The scheme demonstrates rapid convergence for these cases. However, the author does indicate some pre-conditioning had to be utilized in cases presented. The application of this approach to the real design problem will be quite interesting.

7.0 GENERAL COMMENTS

This Technical Specialists' meeting on aerodynamic design and optimization methods was timely and well developed. The program included papers which dealt with most approaches to aerodynamic design and optimization. The subject presentations included what could be termed classical approaches to inverse aerodynamic methods as well as newly developed and highly promising schemes. The program contributions were also from a broad international spectrum and covered a wide variety of applications from the classical airfoil problem to complex turbomachinery problems. This variety indicates the broad base of such applications currently being exercised throughout the global aerospace community.

Clearly, the quality of the studies varied and the quality of the design results also varied. Some authors only reported preliminary results from analytical efforts. If the design or optimization results are modest changes from a base configuraton, it is often hard to prove that the computational configuration refinement is more than bouncing around in the computational and experimental error band. Others reported thorough analytical results backed up by experimental confirmation of the design aerodynamics. This latter completeness is to be commended.

It is obvious that computational design and optimization efforts will continue to grow as pressures for increased automation and design capability are felt. Increased global competition will continue to add such pressures and the design aerodynamicist community will increasingly rely on such methods to improve design efficiency. It is recommended that AGARD continue its interest in such methods and formulate future events for timely dissemination of results on an international scale.

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APPENDIX A
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APPENDIX B
LIST OF PAPERS

PAPER NO.	PAPER
	SESSION I - INVITED & SURVEY PAPERS Chairman: J.W. SLOOFF
1.	Progress in Inverse Design and Optimization in Aerodynamics H. SOBIECZKY, DLR, GE
3.	Aerofoil Design Techniques A.J. BOCCI, ARA, UK
7.	Aerodynamic Design Techniques at DLR Institute for Design Aerodynamics H. KOSTER, C.H. ROHARDT AND K.H. HORSTMANN, DLR Braunschweig, GE
22.	Airfoil Design Using Optimal Control A. JAMESTON, Princeton, USA SESSION II - INVERSE METHODS - AIRFOILS AND WINGS CHAIRMAN: K.L. KUSHMAN
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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AR-267	ISBN 92-835-0557-3	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title TECHNICAL EVALUATION REPORT ON THE FLUID DYNAMICS PANEL SYMPOSIUM ON COMPUTATIONAL METHODS FOR AERODYNAMIC DESIGN (INVERSE) AND OPTIMIZATION

7. Presented at

8. Author(s)/Editor(s)	9. Date
P.A.Henne; Edited by Prof. Ir W.J.Slooff	April 1990

10. Author's/Editor's Address	11. Pages
See Flyleaf.	16

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Computation	Optimization
Fluid dynamics	Reviews
Design	Meetings
Aerodynamic characteristics	

14. Abstract

The papers presented at the AGARD Fluid Dynamics Panel Specialists' Meeting on "Computational Methods for Aerodynamic Design (Inverse) and Optimization" are reviewed. Strengths and weaknesses are identified for many of the contributions as each is reviewed. The reviewer closes with some general comments. The 23 papers presented at the Meeting have been collected in AGARD CP 463. (ADA220 870).

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